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ANALYSIS OF SPACE TUG OPERATING TECHNIQUES

SUPPLEMENTAL REPORT (STUDY 2.4)

THE AEROSPACE CORPORATION

Aerospace Report No.
ATR-73(7314)-2

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Prepared by

Advanced Vehicle Systems Directorate
Systems Planning Division

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Systems Engineering Operations
THE AEROSPACE CORPORATION
El Segundo, California

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FOREWORD

Study 2.4, "Analysis of Space Tug Operating Techniques," was managed by the Advanced Missions Office of the NASA Office of Manned Space Flight. Dr. J. W. Wild was the Technical Director of this study; day-to-day management was performed by Mr. R. R. Carley. Mr. R. E. Kendall was The Aerospace Corporation Study Director from study initiation until 3 April 1972. Dr. L. R. Sitney directed the Study from that date through completion.

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1. INTRODUCTION

This report summarizes the effort expended under Study 2.4, "Analysis of Space Tug Operating Techniques," of Contract NASw-2301 which addressed the subjects of fault detection techniques, sustaining engineering requirements, and off-site facility requirements that result from Tug refurbishment and spares provisioning. This effort was conducted during the last month of the study and was not reported in the Study 2.4 final report, Aerospace report ATR-73(7314)-1.

2. SUMMARY AND CONCLUSIONS

An estimate was made of Tug sustaining engineering requirements for the three phases of the flight program: the flight test phase, the initial operational capability phase (IOC), and the operational capability phase (OC). Only general conclusions can be drawn from this limited survey of sustaining engineering requirements. It is obvious that a significant level of continuing effort will be required in a variety of technical areas. A more in-depth study should result in the development of appropriate data on which more realistic estimates of requirements could be based. In the interim, the values given in this report can be used as examples of manning.

A brief study was performed to determine the off-site feasibility requirements that are necessary for refurbishment and spares support after the manufacturing phase of the program has been completed. It seems reasonable to assume that the Tug prime contractor and the major subcontractors will be from the established major corporations in the aerospace industry. These contractors and their facilities can therefore be expected to be available as needed. The refurbishment/repair facility can be located either on- or off-site. An on-site location involves the provisioning of additional square footage in the maintenance or storage areas. Off-site provisions can be established at the prime contractor's plant or at an existing NASA or DoD facility. A variety of special test facilities will probably be utilized during the program to investigate problem areas. Since it is difficult to identify any problem for which appropriate test facilities will not be available at NASA centers and laboratories, DoD centers and depots, or private industry facilities, no dedicated Tug facilities are visualized.

A brief study was performed to evaluate the advantages of interface comparative testing of identical functional strings of the Tug thrust vector control system as compared with the use of a conventional on-board checkout system

using signal generators and limit tests for determination of status. For the system studied with the selection of tests and the assumptions made, the sizing results conclusively favor the interface comparative test technique over the dedicated on-board checkout technique using signal generators and limit testing. The ratio of sizes (better than 10 to 1) provides a considerable margin for changes in study assumptions without affecting the major conclusions. The results also indicate great promise for extensions of the results to include more subsystems with differing ground rules to firmly prove the validity of the interface comparative approach. If the sizing results can be demonstrated consistent with better failure isolation, major savings in refurbishment costs are feasible. Studies have shown a 50 percent accuracy level for fault isolation on current avionics systems. The gains possible if the fault isolation accuracy level can be increased from 50 percent to 95 percent are obvious, and reduction of required checkout equipment (parts count and weight) by a factor of 10 can affect such a saving.

3. SUSTAINING ENGINEERING

3.1 GENERAL

Sustaining engineering is that continuing technical effort required to support use of the prime hardware - in this case the Tug itself. It is initiated at the conclusion of the original design phase and continues throughout the life of the system.

The types of activity include the analysis and correction of failures or sub-nominal performance, development of temporary fixes and modification kits, software and procedure revisions, product improvement changes, performance analysis, and various functions associated with program management and control. The actual breakdown employed in the analysis is presented below in Section 3.3, Sustaining Engineering Support Categories.

It was assumed that no sustaining engineering would be separately maintained at vendor plants. Any such effort was considered to be incorporated in spares provisioning, although occasional temporary support requirements can be anticipated.

It was recognized that the flight test and initial operational phases would be concurrent with the latter stages of the production activity. The sustaining engineering effort was assumed to be restricted to support of delivered hardware and not to include the usual engineering activity involved in production of the hardware (e.g., engineering orders and drawing changes, liaison engineering, etc.).

3.2 APPROACH

Sustaining engineering requirements for the Tug were divided into three categories: (1) the flight test phase of 5 flights, (2) the initial operational phase of 20 flights, and (3) the operational phase covering the remainder of the life cycle. Each phase is separately addressed in the succeeding sections.

For the purposes of this assessment, the sustaining engineering requirements were limited to identification of direct engineering manning including first level supervision. Indirect support and higher level management were excluded. Also, the turnaround and refurbishment manning were excluded as they are accounted for separately.

The requirements have been identified by Tug subsystem and engineering support groupings in accordance with the technical disciplines involved. This not only permitted a more detailed evaluation, but in addition, assured inclusion of all pertinent engineering effort. Further, the overall accuracy of the projected support should be enhanced through off-setting high and low estimates.

It was also necessary to distinguish between engineering support located at the prime contractor's plant and that located at each of the two launch sites. Each of these locations will have both contractor personnel and government personnel associated with the engineering effort. A third locale at which sustaining engineering will be performed is the responsible NASA center (assumed to be MSFC). Both government and contractor personnel requirements were recognized as part of the total support mix.

The initial nature of the study precluded an adequate acquisition, evaluation, and application of current programs' sustaining engineering experience. This should be made the subject of a more extended analysis in which rational comparison of the Tug to other comparable hardware programs (including aircraft) can be established and manning data from those programs utilized to project a more accurate determination of probable Tug support levels. The figures in this study represent judgemental estimates which are to be considered as more subjective than rigorous and for example purposes only.

3.3 SUSTAINING ENGINEERING SUPPORT CATEGORIES

Sustaining engineering was identified in several discrete groupings of technical categories. These were established according to the usual engineering department functional organization along lines of similar technical effort and specialization. All Tug subsystems are covered as were engineering functions which cut across subsystem lines. The categories are as follows:

- Structure and Stress
- Main Propulsion
- Auxiliary Propulsion and Attitude Control
- Thermal Control
- Electric Power and Control
- Communications and Instrumentation
- Guidance and Navigation
- Flight Control
- Data Processing/Analysis
- Fluid Systems (Hydraulic, Pneumatic)
- Mechanical Systems (including Docking and Ordnance)
- Support Systems (Electrical/Mechanical GSE, Facilities)
- Reliability/Maintainability
- Mission Planning and Performance (Including Weights)
- Configuration Control, Procedures Management Interface Control
- Test Engineering
- Program Control and Management
- General Engineering Support
- Logistics Management
- Technical Liaison/Engineering Representatives

The functional responsibilities of each group should be readily apparent. In some cases, an arbitrary division was made, but an attempt was made to identify all conceivable engineering tasks and to provide a comprehensive support organization.

Software revisions and additions were assumed to be supported by the technical group concerned (e.g., the guidance and navigation group would be responsible for its software changes).

The General Engineering category was established to recognize the support required in specialized technical disciplines such as fluid dynamics, thermodynamics, electronics (many areas), and laboratory support. The level of effort will vary according to discrete real-time requirements and can only be expressed on an equivalent manpower basis. An arbitrary percentage (10 percent) of the total manning was used, but examination of current programs' experience will be required before a defensible projection can be made.

As noted, the categories were established with the prime contractor's in-plant organization in mind, and where separate groups or individuals would be assigned. All of the functional areas are equally applicable to on-site support considerations and to government personnel requirements, although much more consolidation of functional responsibilities was assumed.

3.4 SUPPORT REQUIREMENTS ANALYSIS

3.4.1 Flight Test Phase

The flight test phase, consisting of the first five flights, will require the greatest and broadest level of support. It is during this period that infant mortality effects are felt, with consequent demands for investigation and analysis in all areas. Data acquisition and reduction will be extensive and many procedural changes will be made. Numerous corrective actions will be taken which will affect such areas as configuration management. Initial

flights will uncover flaws in separation, docking and retrieval operations and all Tug subsystems will be reviewed to identify inadequacies or potential improvement. An expanded degree of interest in the payloads community can be anticipated if flights are successful, calling for extended work in the performance and mission applications area. If flights are below expectation, considerable effort will be applied to determining the causes and solutions for sub-nominal performance. A possible manning distribution for this phase is given in Table 3-1. All flights were assumed to be from KSC.

3.4.2 Initial Operational Phase

During this period the next 20 flights are made. There should be a marked drop off in problems involved with the original configuration, but this will be off-set by increased activity due to the higher flight rate, by the introduction of product improvement changes and the development of modification kits. The latter will be both for the purpose of expanding the capability of the Tug and for special adaptations required by payloads. The expanded capability kits may be similar to those provided by the Agena system and include increased electric power, additional telemetry recording and/or transmission capability and refined pointing accuracy. It can also be expected that requests for changes to improve maintainability will increase as experience in turn-around operations builds up.

As noted in the General section, the study excluded that engineering effort involved with the original design release and subsequent production phase support. If it is assumed that production of the Tug fleet is completed by the end of the third year, the sustaining engineering staff will be increased by transfers from the production engineering staff as continuing functions are assumed (design maintenance, shop liaison for spares production, etc.).

The second phase also includes introduction of the second launch site, with an IOC at the beginning of the third year of Shuttle operation assumed. The staff at KSC will be essentially duplicated at VAFB, but with an expansion of the support engineering personnel due to installation and activation of the ground system

Table 3-1. Sustaining Engineering - Manning
Flight Test Phase (5 Flights)

Functional Category	In-Plant		Launch Site KSC		Launch Site VAFB		NASA Center	
	Contr.	Govt.	Contr.	Govt.	Contr.	Govt.	Contr.	Govt.
Structures/Stress	10	-	-	-	-	-	-	2
Main Propulsion	6	-	-	-	-	-	-	3
Auxiliary Propulsion/ Attitude Control	5	-	-	-	-	-	-	2
Thermal Control	6	-	-	-	-	-	-	2
Electric Power and Control	5	-	-	-	-	-	-	2
Communications and Instrumentation	9	-	-	4	-	-	-	3
Guidance and Navigation	12	-	-	-	-	-	-	4
Flight Control	3	-	-	-	-	-	-	1
Data Processing/Analysis	9	-	-	2	-	-	-	5
Fluid Systems (Hydraulic and Pneumatic)	4	-	-	-	-	-	-	1
Mechanical Systems (including Docking, Ordnance)	6	-	-	-	-	-	-	3
Support Systems (Electrical/ Mechanical GSE, Facilities)	10	-	-	6	-	-	-	4
Reliability/Maintainability	5	-	-	1	-	-	-	1
Mission Planning and Performance (including Weights)	6	-	-	1	-	-	-	4
Configuration Control, Procedures Management, Interface Control	8	-	-	3	-	-	-	4
Test Engineering	8	-	-	2	-	-	-	2
Program Control/Management	8	-	-	4	-	-	-	6
Logistics Management	7	-	-	3	-	-	-	4
General Engineering Support (@ 10%)	13	-	-	3	-	-	-	5
Technical Liaison/Engineering Representatives	-	8	6	-	-	-	4	-
TOTAL	140	8	6	29	-	-	4	58
PHASE TOTAL - 245								

Table 3-2 presents an example manning matrix for the early operational phase.

3.4.3 Operational Phase

The remaining years of the program should see a gradual reduction in engineering staff requirements. This will be mostly in launch site and NASA Center manning. In-plant contractor support may be expected to drop off to some degree, but not significantly as modification requests will continue, failed equipment reports will probably accelerate as service time is built up and planning for major overhauls instituted. There should also be a gradual reduction in the technical level of support with a consequent lowering of annual dollars-per-man allocations.

The in-plant contractor reductions will occur mostly in the subsystem support areas. Reliability and maintainability support should continue at the same level with maintainability reductions offset by increased reliability analysis and prediction effort as statistical data builds up. The Configuration Control Group should contract slightly as its functions become more routine, and the Program Control activities should be only moderately affected.

It was assumed that the primary field activity was centered at KSC where the majority of flights take place. Only resident liaison personnel should be required full-time at VAFB.

The manning of the NASA Center will probably drop significantly although the on-going nature of the program and continued modifications proposals will require moderate staffing.

Table 3-3 presents an estimate of anticipated manning for the fully operational phase.

Table 3-2. Sustaining Engineering - Manning
Initial Operational Phase

Functional Category	In-Plant		Launch Site KSC		Launch Site VAFB		NASA Center	
	Contr.	Govt.	Contr.	Govt.	Contr.	Govt.	Contr.	Govt.
Structures/Stress	8	-	-	-	-	-	-	2
Main Propulsion	4	-	-	-	-	-	-	2
Auxiliary Propulsion/ Attitude Control	4	-	-	-	-	-	-	1
Thermal Control	3	-	-	-	-	-	-	1
Electric Power and Control	3	-	-	-	-	-	-	1
Communications and Instrumentation	8	-	-	2	-	1	-	2
Guidance and Navigation	11	-	-	-	-	-	-	3
Flight Control	2	-	-	-	-	-	-	1
Data Processing Analysis	8	-	-	1	-	-	-	3
Fluid Systems (Hydraulic and Pneumatic)	2	-	-	-	-	-	-	1
Mechanical Systems (including Docking, Ordnance)	4	-	-	-	-	-	-	2
Support Systems (Electrical/ Mechanical GSE, Facilities)	7	-	-	4	-	6	-	3
Reliability/Maintainability	3	-	-	-	-	-	-	1
Mission Planning and Performance (including weights)	6	-	-	1	-	-	-	3
Configuration Control, Procedures Management, Interface Control	6	-	-	3	-	3	-	3
Test Engineering	5	-	-	1	-	-	-	1
Program Control/Management	7	-	-	3	-	3	-	3
Logistics Management	6	-	-	2	-	2	-	3
General Engineering Support (@ 10%)	10	-	-	2	-	1	-	4
Technical Liaison/Engineering Representatives	-	6	4	-	3	-	4	-
TOTAL	107	6	4	19	3	16	4	40
PHASE TOTAL - 199								

Table 3-3. Sustaining Engineering - Manning Operational Phase

Functional Category	In-Plant		Launch Site: KSC		Launch Site: VAFB		NASA Center	
	Contr.	Govt.	Contr.	Govt.	Contr.	Govt.	Contr.	Govt.
Structures/Stress	6	-	-	-	-	-	-	1
Main Propulsion	2	-	-	-	-	-	-	1
Auxiliary Propulsion/ Attitude Control	2	-	-	-	-	-	-	1
Thermal Control	2	-	-	-	-	-	-	1
Electric Power and Control	2	-	-	-	-	-	-	1
Communications and Instrumentation	6	-	-	2	-	-	-	2
Guidance and Navigation	10	-	-	-	-	-	-	3
Flight Control	2	-	-	-	-	-	-	1
Data Processing/Analysis	6	-	-	1	-	-	-	2
Fluid Systems (Hydraulic and Pneumatic)	2	-	-	-	-	-	-	1
Mechanical Systems (including Docking, Ordnance)	3	-	-	-	-	-	-	1
Support Systems (Electrical/ Mechanical GSE, Facilities)	4	-	-	3	-	1	-	2
Reliability/Maintainability	3	-	-	-	-	-	-	1
Mission Planning and Performance (including Weights)	5	-	-	-	-	-	-	2
Configuration Control, Procedures Management, Interface Control	5	-	-	2	-	1	-	2
Test Engineering	3	-	-	-	-	-	-	1
Program Control/Management	6	-	-	2	-	2	-	2
Logistics Management	4	-	-	1	-	1	-	2
General Engineering Support (@ 10%)	7	-	-	1	-	-	-	3
Technical Liaison/Engineering Representatives	-	5	3	-	1	-	4	-
TOTALS	80	5	3	12	1	5	4	30
PHASE TOTAL - 140								

3.5 TYPICAL EXPENDABLE STAGE

An example of sustaining engineering requirements for a current expendable vehicle is shown in Table 3-4. The particular contractor does not identify a significant level of effort as "sustaining engineering," but rather is organized into separate program support groups. Further, the various programs employing the vehicle are frequently those in which the contractor is prime for both the vehicle and the payload and, therefore, the manning is also concerned with the payload itself. It was consequently difficult to single out purely vehicle engineering support. Only contractor requirements are given, and general engineering support is not identified. The contractor organization includes auxiliary propulsion and attitude control in the Flight Control category so a separate figure is not given for the former. Also, several of the categories include allowances for computer simulation work, including software development. The figures are considered typical of a fully operational phase.

Table 3-4. Typical Expendable Stage Sustaining Engineering

Functional Category	In-Plant		Launch Site				NASA Center	
			KSC		VAFB			
	Contr.	Govt.	Contr.	Govt.	Contr.	Govt.	Contr.	Govt.
Structures/Stress	6-7							
Main Propulsion	2							
Auxiliary Propulsion/ Attitude Control	-							
Thermal Control	4							
Electric Power and Control	5							
Communications and Instrumentation	8							
Guidance and Navigation	12-14							
Flight Control	5							
Data Processing/Analysis and Software	6							
Fluid Systems (Hydraulic and Pneumatic)	1							
Mechanical Systems (including Docking, Ordnance)	5							
Support Systems (Electrical/ Mechanical, GSE, Facilities)	4-5							
Reliability/Maintainability	6-7							
Mission Planning and Performance (including	5							
Configuration Control Procedures Management, Interface Control	5							
Test Engineering	3							
Program Control/Management	8							
Logistics Management	4							
General Engineering Support	N. A.							
Technical Liaison/Engineering Representatives							3	
TOTAL	89-94	-	0	-	-	-	3	-
PHASE TOTAL -								

4. OFF-SITE FACILITY REQUIREMENTS

4.1 REFURBISHMENT SUPPORT

There are two major specialized facility requirements for Tug refurbishment, a vacuum chamber and a Tug maintenance/refurbishment facility. The vacuum chamber must be large enough to house the Tug and have the capability to obtain a vacuum of 10^{-3} torr. No cold-wall or heat lamp capability is required. The vacuum chamber is used primarily in the periodic verification of the propellant tank insulation system and could be located on-site or off-site. The refurbishment/maintenance facility must provide the necessary square footage and equipments required for Tug maintenance. The extent of the facility requirements is dependent on the degree of maintenance performed.

The approach taken in this refurbishment study is a combination of on-site and off-site refurbishment. Routine maintenance such as visual inspections, functional checks, leak checks, minor recalibrations, etc., is performed after every mission at the launch site maintenance facility. At periodic intervals or whenever a failure occurs, the equipment is removed from the vehicle and sent to a refurbishment/repair facility for a tear-down inspection or repair. This refurbishment/repair facility could be an integral part of the on-site maintenance facility, a separate facility at the launch site, or an off-site facility. The results of the refurbishment study are independent of the location of the refurbishment/repair facility since the cost of refurbishment or repair of the piece of equipment was assumed to be a percentage of the cost of a new unit. Off-site facilities could be established at the Tug prime contractor's plant or at an existing NASA or DoD facility. In any case, a dedicated facility is not considered to be required.

For example, the main engine is inspected and minor calibration and adjustments are made after each flight at the maintenance facility at the launch site. After 5 hours of operation (10 missions), the engine is removed from the vehicle and returned to the engine manufacturer for a tear-down inspection.

After 10 hours of operation (20 missions), the engine is removed from the vehicle and returned to the manufacturer for a complete overhaul. The off-site facility requirements would be normal engine assembly and disassembly areas (clean rooms) and a test stand for engine firing. These facilities are not considered to be dedicated, only facilities that are used by the contractor for other development and hardware programs.

Other vehicle areas, such as avionics, auxiliary propulsion, electrical power, propellant tank insulation system, etc., should not require any dedicated off-site facilities. The equipment that will be required consists of the usual equipment utilized for assembly and checkout during the manufacture of the hardware and could, for the most part, be utilized for other hardware programs. No specialized equipment needs are anticipated. If the original manufacturer is utilized for the refurbishment/repair function, no additional facilities will be required; however, if a separate maintenance contractor is used, the facilities must include all of the equipment necessary for disassembly, assembly and checkout of the hardware. This would require duplication of most of the equipment used by the original manufacturer during the production of the hardware. Hence, to minimize the off-site facility requirements, any off-site repair or refurbishment of hardware should be done by the original manufacturer.

It seems reasonable to assume that the Tug prime contractor and major subsystem contractors will be from the established major corporations of the aerospace industry. These contractors and their facilities are assumed to be available as needed during the Tug operational phase. A variety of special test facilities will probably be utilized during the program to investigate unique problem areas. It is difficult to identify any problem for which appropriate test facilities will not be available at NASA centers and laboratories, DoD centers and depots or private industry facilities; therefore, no dedicated Tug facilities are visualized.

4.2 SPARES SUPPORT

The extent of off-site facility requirements that result from spares support is a function of the approach taken in spares provisioning. Two approaches to spares support are: (1) buy all of the spares at the beginning of the program, and (2) purchase the spares from the original manufacturer over the life of the program on an as-needed basis. The first approach would appear to have the least impact on the support requirements; however, it would only be feasible if the question of what and how many spares would be required during the life of the program could be answered. The unknowns involved relative to the maintainability and reusability of the various Tug systems make this question difficult to answer. Vehicle modifications required by either early design glitches or design changes brought about by technological advances later in the operational program could result in the obsolescence of spares that were purchased at the beginning of the program. Another problem with purchasing all the spares at the beginning of the program has to do with peak funding. The cost of purchasing the spares required over a ten to twenty year period could be significant. On the other hand, the early purchase of spares does have the advantage that one does not have to be concerned about whether or not the original manufacturer will still be in existence 5 or 10 years later to build the particular spare item when it is needed.

The purchase of spares over the life of the program on an as-needed basis could be expensive since this would require the manufacturer to maintain a production capability after the main production run has been completed. This approach requires that the manufacturer remain in business for the life of the program. This assumption may be valid for the Tug prime contractor and the major subcontractors but not necessarily for many of the smaller contractors.

The approach to spares provisioning which appears to have the least impact on the total spares support requirements is one which is a combination of the two approaches described in the previous paragraphs. During the initial

manufacturing phase of the program when the flight test vehicles are being produced, an over-buy of the anticipated spares required would be made. Then, if these spares are not needed, they could be utilized in the production of the remaining flight vehicles. Hopefully, before the production of all the vehicles has been completed, enough experience will have been gained during the flight test program and early operational flights to permit a better estimate of the spares required. Later, in the operational phase of the program if a need develops for some additional spares or vehicle modifications, the customer could ask for competitive bids. In order to be in a position to do this, the customer must purchase from the original manufacturer at the beginning of the program all of the necessary drawings, specifications, test equipment specifications, etc. Hence, the customer does not necessarily have to depend on the original manufacturer remaining in business nor does he have to accept the original manufacturer's price for additional spares.

5. EVALUATION OF TUG CHECKOUT ALTERNATIVES: INTERFACE COMPARATIVE VS DEDICATED ON-BOARD CHECKOUT

5.1 OBJECTIVES

To perform its mission, the Tug must implement the functions of data management; guidance, navigation and control; rendezvous and docking; communication; electrical power generation, conversion and distribution; etc. Each of the subsystems employs triple or quadruple redundancy to insure mission success and each subsystem must be checked for readiness before deployment and for operability during flight. The objective of this effort is to evaluate the relative merits (size, weight and power) of two checkout alternatives: (1) interface comparative, and (2) dedicated on-board checkout.

5.2 APPROACH

Because of the short period of time available, a decision was made to limit this evaluation to one subsystem, the thrust vector control subsystem. This subsystem is a critical one of moderate complexity for which results may be extended to other subsystems with a significant degree of assurance.

To provide a realistic set of test requirements and associated test points, the testing of a similar operational subsystem, the thrust vector control system of the Titan IIIC second stage was examined in detail. Each test performed on that vehicle was examined for applicability to the Tug and a set of tests was defined as the basis for the checkout system comparisons.

A sizing effort was completed for the interface comparative and the dedicated on-board checkout system. Conclusions from quantitative comparison of the two alternatives are described with recommendations and qualitative comments.

5.3 DISCUSSION

5.3.1 Titan IIIC Second Stage Thrust Vector Control System Testing

Figure 5-1 depicts the ground and airborne equipment associated with testing of the second stage of the Titan IIIC. There are many similarities between the equipments employed on board and the operating environment of the stage with the current planning for the Tug thrust vector control subsystem. A major difference is the requirement for ground checkout only for Titan IIIC whereas the operational mode of the Shuttle provides a later opportunity for checkout and a concomitant requirement for some checkout of the Tug on orbit to insure a safe return of the vehicle inside the Shuttle. Nevertheless, it was felt that an examination of the test requirements prior to launch of the Titan IIIC (see Appendix A for details) would provide a logical basis for a realistic set of test requirements for the planned on-board checkout system of the Tug. A complete description of the tests examined is presented in Appendix A and the results of this examination are summarized in Table 5-1 with the rationale for the tests selected.

In addition to the tests selected from the Titan set, provisions for dynamic response testing were also included in the comparison repertoire.

Another significant point relative to the Titan testing which will influence the test planning for the Tug is the approach to testing of the digital computer serial elements in the flight control system. With a digital computer providing the autopilot function in the flight control system (FCS), software takes the place of hardware for mechanization of filters and gain requirements. The responsibility in checkout is to functionally verify FCS hardware utilizing equations (software) and to assume the flight software is valid. This approach employs an end-to-end FCS hardware test that utilizes simple software equations that are separate from the flight equations. This end-to-end FCS hardware test demonstrates that each flight control sensor and actuating device is performing in an acceptable manner, and that the

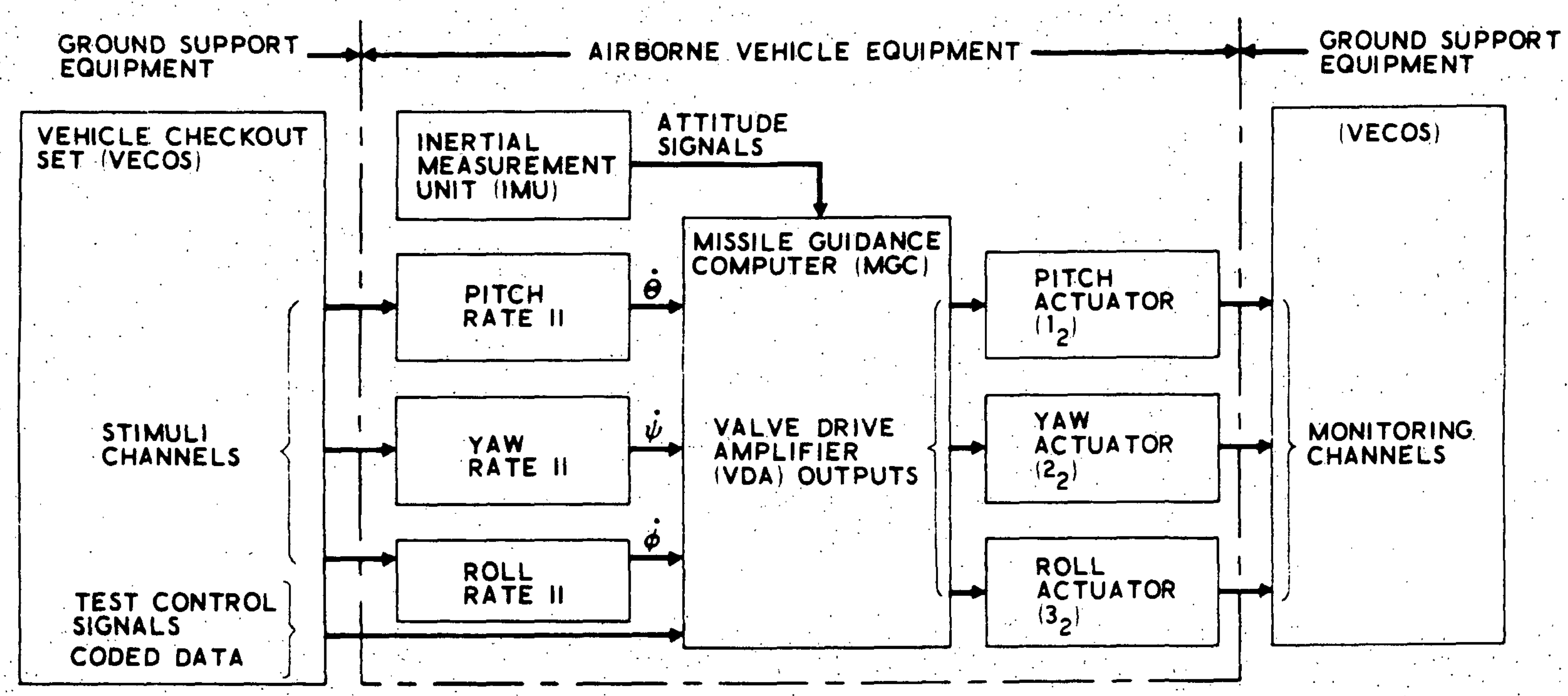

Figure 5-1. Titan IIIC Stage II Flight Control System, Simplified Block Diagram

Table 5-1. Titan Flight Control System Tests

Test	Applicable to Tug Checkout Comparison Study	Rationale
1. Gyro Temperature and Spin Motor Rotation Detection	No	Sensors are included in guidance system for Tug--not flight controls
2. Flight Control Phasing Tests	No	This test is a one-time test conducted on initial system installation
3. Engine Alignment Verification	No	Same as 2, above
4. Dynamic Cross Coupling Test	Yes	
5. System Nulls and Static Gains	Yes	
6. Automatic Vehicle Verification	Partially	Success criteria requiring engineering evaluation of analog recordings must be designed out
7. Valve Drive Amplifier Stability Test	No	This test developed as a result of a design deficiency and is vehicle-peculiar
8. Signal Interface Test	No	This is a one-time test at equipment installation

interconnections between the FCS elements are correct. The flight control hardware end-to-end test philosophy is only acceptable when a software validation program complements the hardware tests, and integrity of the flight software is demonstrated in open loop tests and closed loop trajectory simulations.

5.3.2 Comparison of Interface Comparative and Dedicated On-Board Checkout Systems

5.3.2.1 Definition of Checkout Systems

The interface comparative technique of testing is based on the principle that the likelihood of failures in multiple identical subassemblies is very low. The comparative technique employs a majority vote (MV) decision to determine the correct action. Figure 5-2 shows in block diagram form the MV mechanization. The detail implementation of the MV block may be inferred from Ref. 1. When any two "X" units are in agreement, one of the two good inputs to the MV is accordingly transferred to the three outputs. The failed unit is identified to the user by the monitoring point. If subsequent failure is detected (erratic behavior of the Tug) in the case of the control system, an arbitrary guess may be made to select one of the two last known good units by exercising an appropriate bypass control line. For example, if X_1 and X_2 were last known to be good but one has since failed, it may be presumed that either the X_1Y_1 or the Y_2Y_2 bypass discrete may be issued to deactivate the MV decision logic and enable direct transfer of the selected "X" signal to all the "Y" inputs. (The other two "X" outputs are disabled by interrupting power to appropriate units in the preceding chain.) If erratic behavior is not eliminated, the next bypass discrete can be tried.

The dedicated "On-Board Checkout" technique is patterned after the more conventional approach employing a signal generator to stimulate the subsystem. The subsystem responses are measured and evaluated. It has become standard practice to use on-board computers to generate the stimulus for checkout. Ground checkout equipment is used for bulk storage of

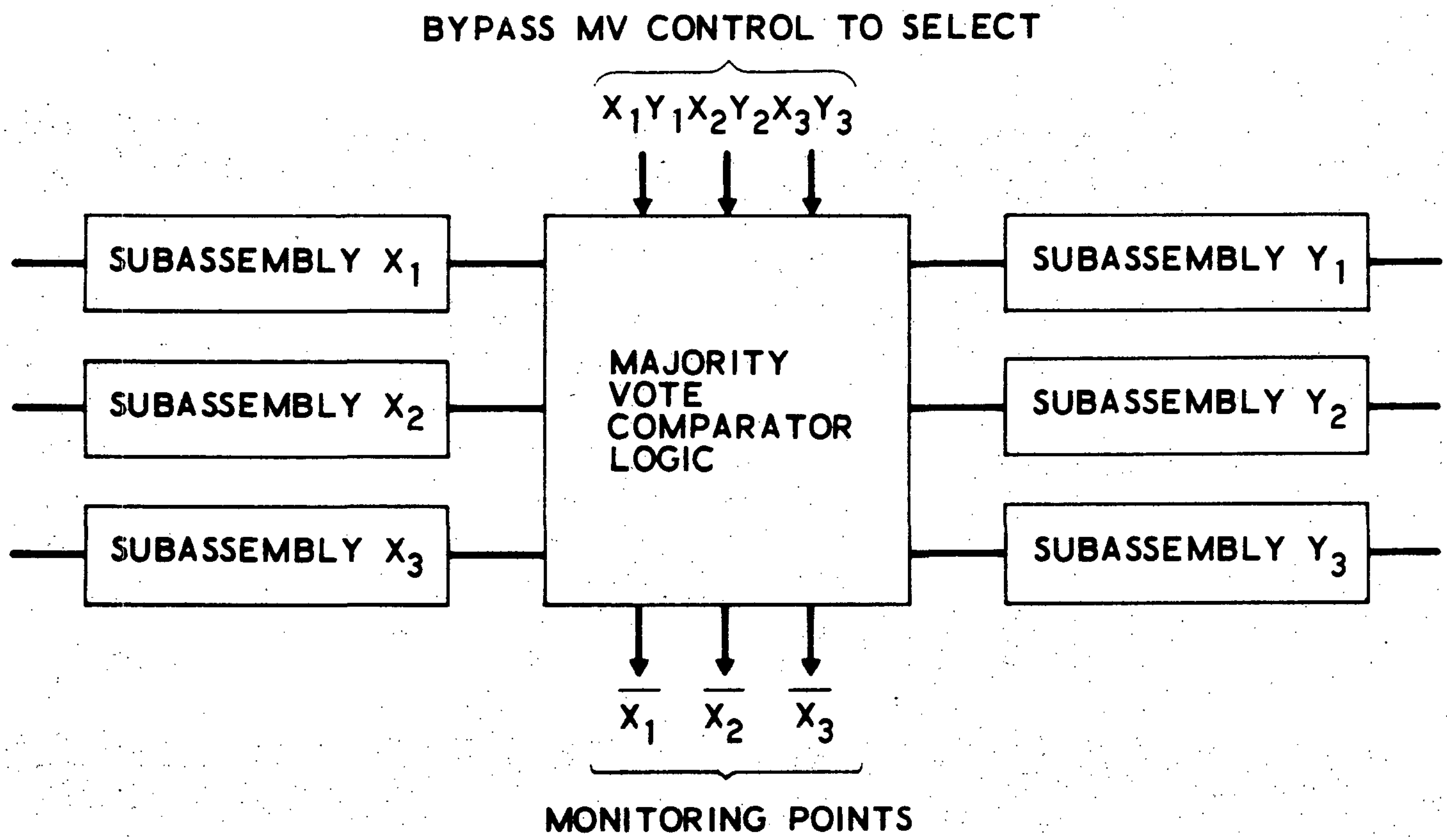

Figure 5-2. Majority Vote Failure Detection

checkout programs (for transfer to on-board computers) and for measuring and recording the test results (the checkout programs are replaced by flight programs after completion of checkouts). For the purposes of this study, the on-board checkout function of each redundant subsystem will be performed by a special purpose microcomputer peculiarly dedicated to each subsystem. The general configuration is shown in Figure 5-3.

5.3.2.2 System Objectives and Assumptions

It is assumed that the checkout system should have the following capabilities:

a. monitor performance

b. evaluate performance

c. report malfunction

d. disable (or inhibit) failed units by power shutdown

It is also assumed that the subsystem reliability requirements will be achieved by triple redundancy for the control system error amplifier and torque motors and by dual redundancy of the actuators.

Performance parameters to be monitored and evaluated are: system nulls, static gains, dynamic gains, interference from other subsystems, etc., as noted previously. Either actual or simulated attitude and rate inputs will be used in checkout. It should be noted that checkout objectives as set forth represent the minimum necessary to establish a valid comparison between the alternative checkout schemes. The design status is at a concept level based on the inexact nature of the existing requirements. Nevertheless, an attempt will be made to arrive at valid equipment comparisons for the two approaches.

5.3.2.3 Study Configurations

The reference concept is shown in block diagram form, Figure 5-4. This configuration is taken from a North American Rockwell report (Reference 3) and represents in approximate form the comparative or majority vote concept.

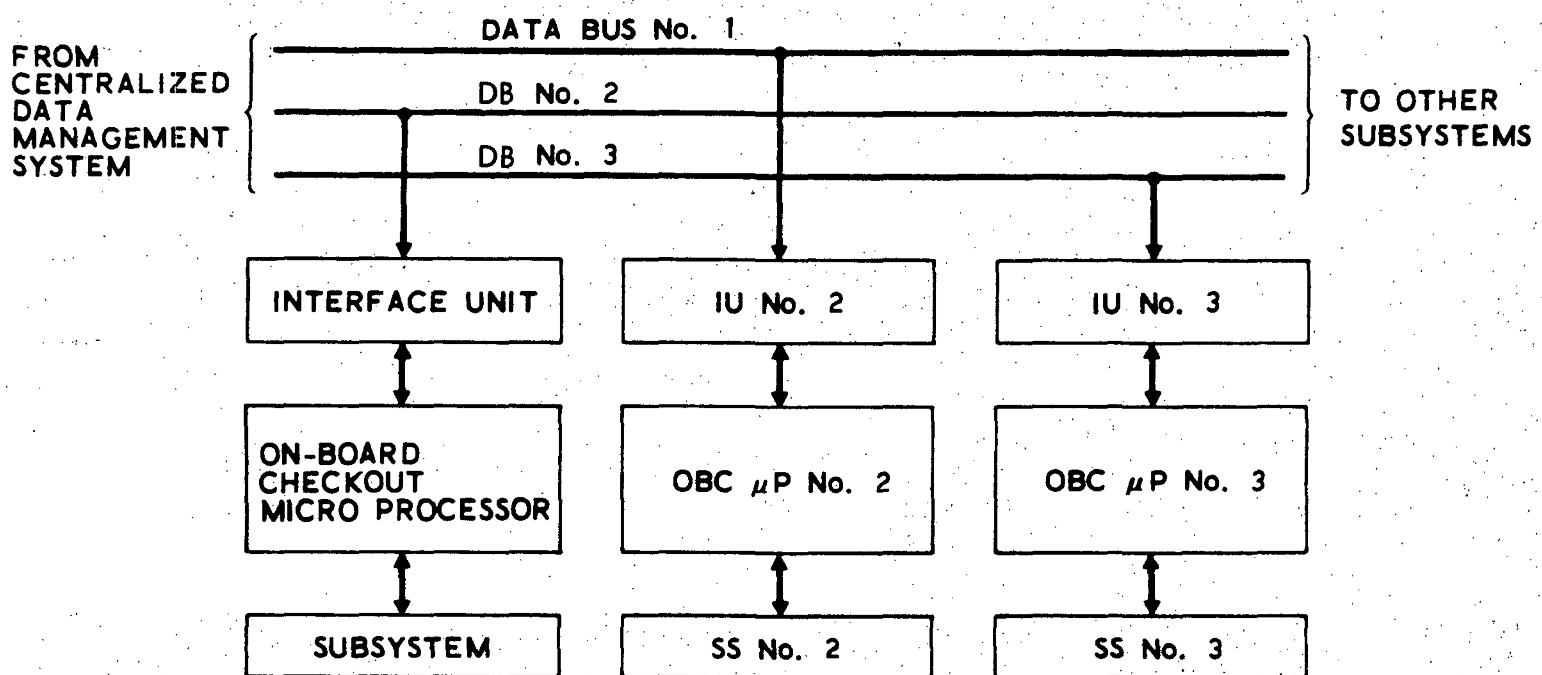

Figure 5-3. Dedicated On-Board Checkout System Diagram

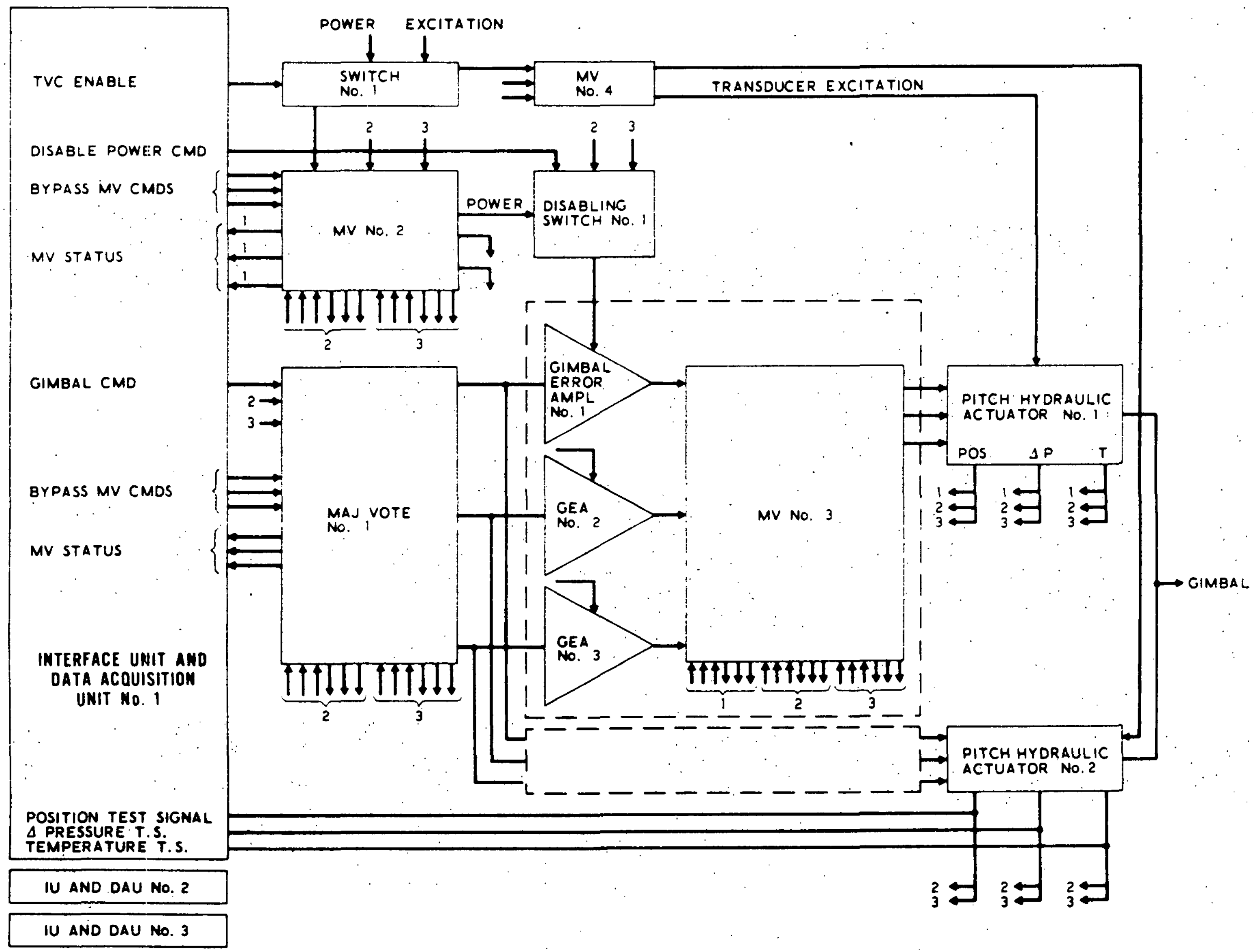

Figure 5-4. Engine Gimbal Servoamplifier Mechanization With Majority Vote Failure Detection

The transducer excitation voltage is for measurement only to show the response of the redundant actuators. The servoactuators are majority voting mechanical feedback servoactuators. Any two correct gimbal error inputs will override the other. (A complete description of the MV actuator may be found in Ref. 2.) Actuators are provided redundantly, two for pitch and two for yaw (it is assumed that roll control will be accomplished by a separate subsystem).

The dedicated on-board checkout concept is shown in Figure 5-5. An examination of Figures 5-4 and 5-5 shows that the differences amount to a microprocessor vs the MV circuits. The microprocessor, of necessity, performs the functions of the Data Acquisition Unit (DAU) (Ref. 3) which are:

a. Sample analog discrete and serial (if appropriate) digital signals from the subsystem and process and buffer store these data for subsequent transfer to the control computer (a part of the data management subsystem (DMS)).

b. Output discrete and serial (if applicable) digital signals to the subsystem under direct control of the DMS computer.

c. Output analog signals under direct control of the DMS computer.

d. Be programmable by the DMS computer via the data bus with 31 instructions (instructions call for signal generation and measurement sampling).

The DAU and control subsystem function during checkout as if in the operational mode. Instructions to enable the actuators and drive the gimbals are received and responded to during all checkout phases (it is assumed that the DMS responds in turn to commands received via the communications subsystems so that on-board programs are not required in the DMS for checkout of the control subsystem). The checkout function and performance verification is accomplished passively by the MV circuits. Any out-of-tolerance

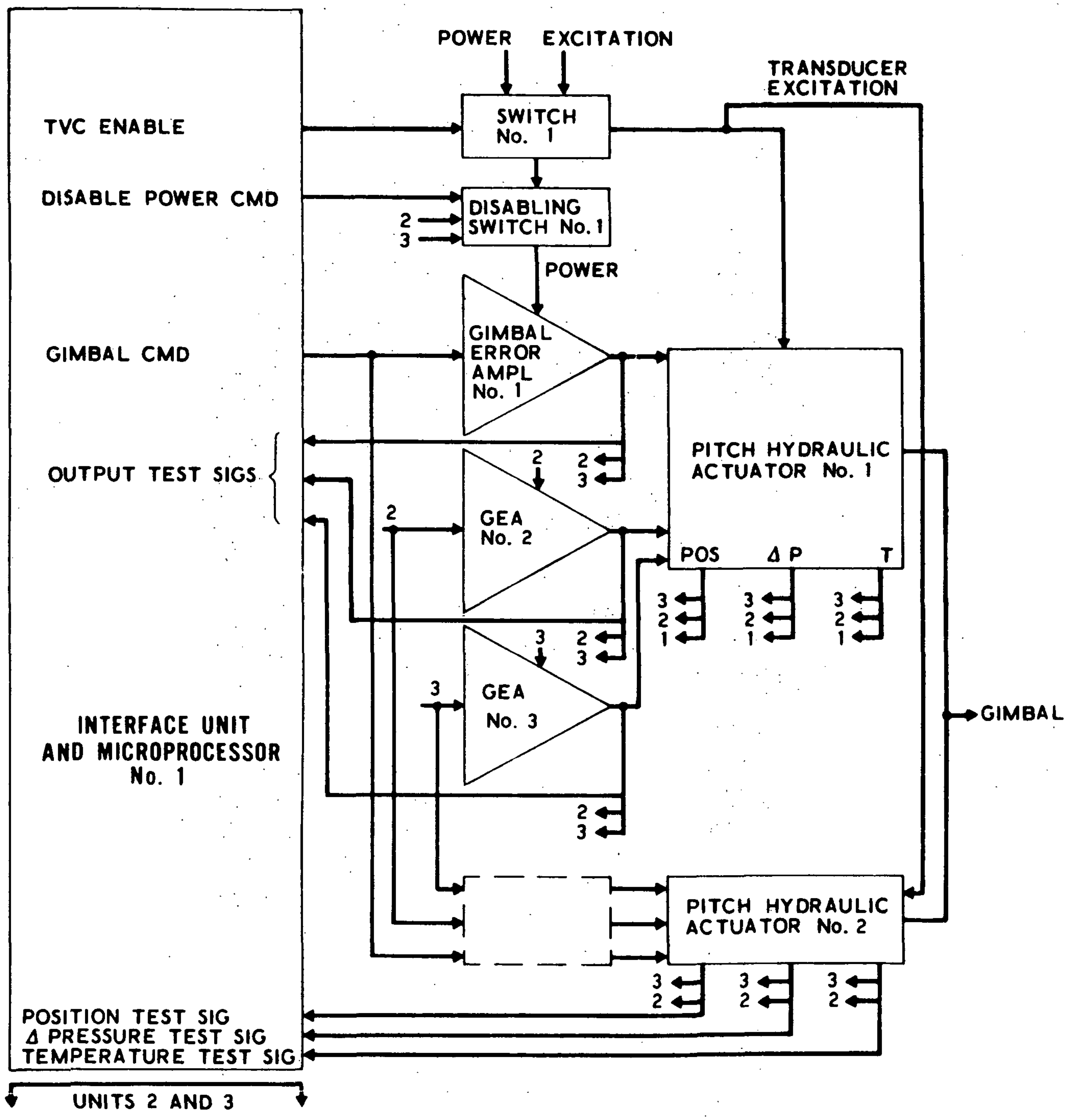

Figure 5-5. Engine Gimbal Servoamplifier Mechanization With Microprocessor Dedicated On-Board Checkout

condition is reported and failed units may be replaced (before boost) or bypassed by the issuance of an appropriate bypass control discrete. (Bypassing calls for a considered judgment in the case of multiple failures prior to deployment of the Tug but after deployment bypassing will enable completion of the mission for failure, for example, of up to 4 of the 6 yaw actuator signal drives).

The microprocessor approach must also accomplish the function of the DAU. In addition, as shown in Figure 5-5, in the absence of majority vote, the dedicated microprocessor must monitor and evaluate the performance of the subsystems. For the sake of equal comparison it will be assumed that instructions for enabling the actuator and driving the gimbals are received via the data bus from the DMS computer.

The computer must store the transfer function for the gimbal error amplifier (GEA) and for the actuator responses. The GEA signal is picked off at the input to the torquers and the actuator response is determined from position and delta pressure transducer outputs. The number of instructions and data words required for these functions have been estimated (Ref. 3, 4, and 5) and a number of microprocessors are available with adequate capability for the checkout function.

5.3.2.4 Microprocessor Sizing-Dedicated Checkout

For the purposes of this study, the microprocessor size will be taken from Ref. 4. With triple redundancy, three microprocessors of the CDC 469 type will be required. This computer is a 10.2 cm (4 in) cube, weighs 1.8 kg (4 lb) and takes 4 watts of power. The standard input/output of this machine will have to be redesigned to include the DAU function. Since the standard I/O is a negligible fraction of the CDC 469, it will be ignored; it is assumed that an increment will be added to the CDC 469 to accomplish the DAU function. Therefore, since both checkout approaches have approximately the same hardware for DAU functions, the comparison will be between the processor and the majority vote hardware.

5.3.2.5 Majority Vote Sizing-Interface Comparative Checkout

Figure 5-6 shows an approximation of the circuitry required for the MV #3 block shown in Figure 5-4. A count of gates indicates that the logic of this function can be accomplished on a large scale integration chip (less than a hundred gates). It is assumed that three operational amplifiers will be required to condition the output signal. The total for yaw and pitch is 12. Nine signal conditioners are provided for status on each MV module (for a total of 90 signal conditioners peculiar to MV for yaw and pitch). Figure 5-4 indicates that 5 MV modules are required for the 2 pitch actuators. Yaw and pitch will have 10 LSI chips total for MV. Thirty-six test signals (pressure, position and temperature) will also have signal conditioners (not shown because they will also be provided for in the dedicated checkout system). It is estimated that a total of 12 opamps, 10 LSI MV chips and 90 signal conditioners (for instrumentation of MV status) will be used uniquely as a part of the MV function. It is estimated that this circuitry will take less than 2.0 watts and can be mounted on one or two multilayer, 10.2 cm x 10.2 cm (4 in x 4 in) motherboards and weigh no more than 100 grams.

5.3.3 Extension of Results and Recommendations

5.3.3.1 Significance of Results

The conclusion of the study effort, namely that the interface comparative technique affords a size advantage of better than 10 to 1 over the conventional dedicated on-board checkout technique, is very significant. Previous examination of checkout system performance in terms of accuracy of fault isolation has clearly demonstrated that major costs are associated with removal from vehicles of non-faulty components. Quoting from Reference 6 by McDonnell Douglas, "It is shown that regardless of the aircraft manufacturer, 54 percent of all autopilot LRUs (Line Replaceable Units) removed from aircraft were not faulty when they were removed." For other subsystems, corresponding percentages are Air Conditioning - 35%, Electrical Power - 37%,

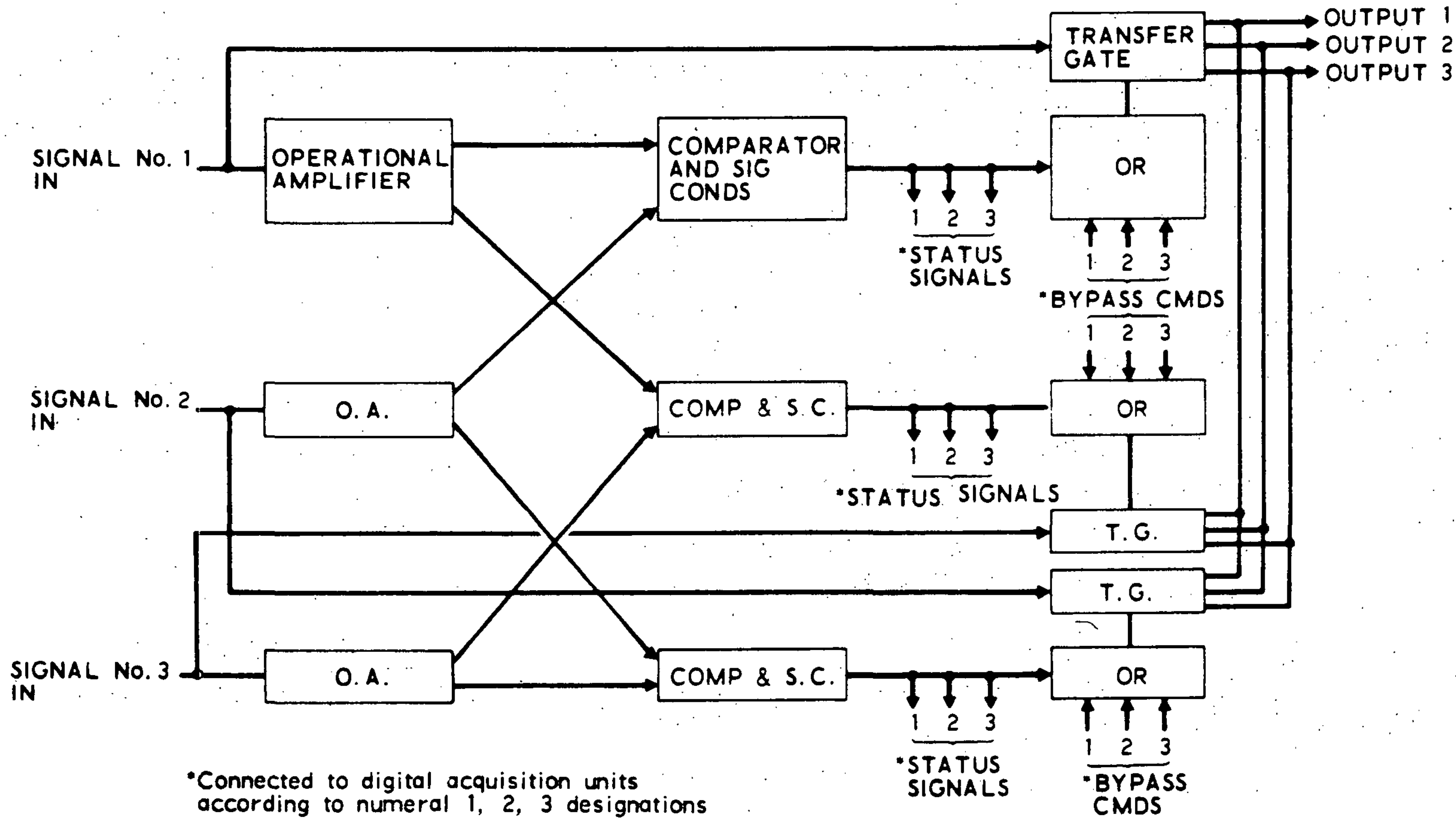

Figure 5-6. Majority Vote Mechanization

Engine Instruments - 45%, and Navigation System - 54%. Improving the fault isolation accuracy level to approximately 95% is predicted to result in a 15% to 20% reduction of total direct maintenance costs.

Since many of the false removals are caused by faulty test equipment, a test technique which reduces, by a large factor, the required number of test equipment piece parts can significantly improve the accuracy of fault isolation (assuming equal capability of the test system with its displaced predecessor) with a corresponding reduction in maintenance costs.

5.3.3.2 Suggested Further Efforts

The sensitivity of the results of this effort to the assumptions made in generation of the data was not examined due to the brevity of the effort. A few of the areas needing clarification include: (1) the validity of the assumption that the communication system originates test sequences rather than on-board programs in the data management system, and (2) the effect on the conclusions of selecting a centralized checkout approach for the dedicated system rather than using microprocessors.

With confidence that these clarifications will confirm the superiority of the interface comparative technique for the thrust vector control system, the applicability of the technique to the total problem of checkout of the Tug on as broad a basis as possible should be considered. The potential for reducing refurbishment costs by streamlining the testing should receive major attention in a study integrating airborne system Tug design with on-board checkout system design, ground system facilities, and refurbishment planning. The interface comparative test approach must be integrated with consistent airborne system design and reliability requirements and maintenance planning to fully recognize its potential for cost savings.

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1. Methods of Improving System Reliability by Use of Redundancy, Final Report, TOR-0059(6758-03)-7, The Aerospace Corporation (13 July 1970)

2. Majority Voting Mechanical Feedback Servoactuator for Saturn S-IVB, MOOG Servocontrols, Inc. (22 July 1965)

3. Final Report, Appendix 3, Avionics DOD Upper Stage/Shuttle System Preliminary Requirements Study, SAMSO-TR-72, North American Rockwell (August 1972)

4. On-Board Checkout for Space Transportation System, TOR-059(6758-02)-7, The Aerospace Corporation (1 July 1970)

5. Space Transportation System Avionics System's Data Base, TOR-0059(6759-03)-9, The Aerospace Corporation (1 July 1970)

6. DC-10 Fault Isolation, DAC-68447, McDonnell Douglas Corporation (14 October 1969)

APPENDIX A. TITAN IIIC THRUST VECTOR CONTROL SYSTEM TESTS

GLOSSARY

ACDE	A C Delco Electronics
APS	Auxiliary Power Supply
DFCS	Digital Flight Control System
DRS	Data Recording Set
FCS	Flight Control System
IGS	Inertial Guidance System
MGC	Missile Guidance Computer
SAPS	Switched Auxiliary Power Supply
SMRD	Spin Motor Rotation Detection
TLM	Telemetry
VDA	Valve Drive Amplifier
VECOS	Vehicle Checkout Set
VV	Vehicle Verification

APPENDIX A. TITAN IIIC THRUST VECTOR CONTROL SYSTEM TESTS

A. 1 GYRO TEMPERATURE AND SMRD (SPIN MOTOR ROTATION DETECTION) DISCRETE VERIFICATION

A. 1. 1 Objective

To verify the time required for gyro heater and SMRD discretes to turn on.

A. 1. 2 Prerequisites

None required.

A. 1. 3 Configuration

None required.

A. 1. 4 Constraints

None required.

A. 1. 5 Test Description

A. 1. 5. 1 Temperature

Apply gyro heater power and measure the time for the gyro heaters discrete to turn On.

A. 1. 5. 2 SMRD

Apply APS power and measure the time for the SMRD discrete to turn ON.

A. 1. 6 Success Criteria

Temperature "Go" discrete shall occur within 40 minutes of application for gyro heater power. At the Site, the discrete may cycle for a total of one hour from first receipt of temperature GO. SMRD "Go" discrete shall occur within 45 seconds of application of APS Bus Voltage

A. 2 FCS PHASING TESTS

A. 2. 1 Objective

To verify proper end-to-end phasing of Flight Control Systems.

A. 2. 2 Prerequisites

Hydraulic system servicing complete.

A. 2. 3 Configuration

None required.

A. 2. 4 Constraints

Requires proper mechanical phasing.

A. 2. 5 Test Description

The flight controls components shall be mechanically displaced to simulate vehicle motion while observing the output. The flight controls components shall be electrically torqued and proper phasing verified at the actuators.

A. 2. 6 Success Criteria

Mechanical phasing shall be in accordance with established values. Electrical phasing shall be in accordance with established values.

A. 3 ENGINE ALIGNMENT VERIFICATION

A. 3. 1 Objective

To verify that the Stage II actuators are properly rigged.

A. 3. 2 Prerequisites

Vehicle erected.

A. 3. 3 Configuration

Actuators connected to the engines.

A. 3. 4 Constraints

None required.

A. 3. 5 Test Description

Measure the attitude of the Stage II engines relative to vehicle centerline.

A. 3. 6 Success Criteria

Engine alignment within acceptable limits.

A. 4 DYNAMIC CROSSCOUPLING TEST

A. 4. 1 Objective

Verify cross channel response stays within acceptable limits when selected signals are introduced into adjacent channels.

A. 4. 2 Prerequisites

None required.

A. 4. 3 Configuration

TLM operating.

A. 4. 4 Constraints

None required.

A. 4. 5 Test Description

Introduce selected signals for pitch-to-yaw, pitch-to-roll, roll-to-yaw, yaw-to-roll, roll-to-pitch, and yaw-to-pitch crosscoupling for Stage II FCS channels.

A. 4. 6 Success Criteria

Dynamic crosscoupling shall not exceed 5 percent of channel response.

A. 5 SYSTEM NULLS AND STATIC GAIN TEST

A. 5. 1 Objective

To verify the system nulls and static gains are within limits.

A. 5. 2 Prerequisites

Hydraulic servicing complete.

A. 5. 3 Configuration

None required.

A.5.4 Constraints

None required.

A.5.5 Test Description

Measure FCS nulls with all inputs connected. Apply FCS stimulus to the sensor or computer and measure the output response for both positive and negative inputs.

A.5.6 Success Criteria

System nulls and static gains shall be verified to be within the limits specified.

A.6 AUTOMATIC VEHICLE VERIFICATION

A.6.1 Objective

To verify the functional integrity of the flight controls system and selected other vehicle functions.

A.6.2 Prerequisites

None required.

A.6.3 Configuration

DRS and TLM operating. VECOS Automatic VV tape installed.

A.6.4 Constraints

At no time will Inertial Guidance System (IGS) power be applied or removed from the vehicle with hydraulic pressure applied.

A.6.5 Test Description

The vehicle verification shall be performed automatically utilizing the Vehicle Checkout Set.

A. 6. 6 Success Criteria

A. 6. 6. 1 Automatic Verification

Verify GO and VEHICLE GO indications occur as required in the proper frames.

A. 6. 6. 2 Interference Susceptibility

Lack of interference susceptibility shall be ferified as follows: Performance of a successful vehicle verification with other subsystems operating. Analog recordings shall indicate an interference level less than five percent of full scale.

A. 7 VALVE DRIVE AMPLIFIER (VDA) STABILITY TEST

A. 7. 1 Objective

To determine the relative stability of the combination of the MGC VDA and vehicle wiring.

A. 7. 2 Prerequisites

Proper operation of the test tool shall be verified using an external 50 ohm $\pm$ 1% resistor.

A. 7. 3 Configuration

IGS AND SAPS power must be OFF. The flight article MGC shall be installed. Stage II, hydraulic actuators shall be electrically connected with hydraulic power OFF.

A. 7. 4 Constraints

None required.

A. 7. 5 Test Description

A. 7. 5. 1 Power Off Test

Power must be OFF and vehicle must be disconnected. The marriage of the ACDE test tool to the MGC with IGS power OFF and vehicle wiring from

the MGC to the actuators disconnected shall be verified by driving the VDA with a constant current step provided by the ACDE test tool and photographing the response as shown by an oscilloscope across a 51.6 ohm monitor resistor. Both a positive and negative going step response for any one of the nine VDAs shall be photographed.

A.7.5.2 Power On Test

Power must be ON, vehicle connected, umbilicals ON. The transient response at the MGC VDA loaded by vehicle wiring including the VECOS malfunction isolation monitor lines shall be verified by driving the VDA with a constant current step provided by the ACDE test tool and photographing the response as shown by an oscilloscope going step response for all three VDA s shall be photographed.

A.7.5.3 Umbilicals Disconnected

Power ON, vehicle wiring connected, umbilicals disconnected. The transient response of the MGC VDA loaded by in-flight vehicle wiring (i.e., with VECOS lines disconnected) shall be verified.

A.7.6 SUCCESS CRITERIA

A.7.6.1 Power Off Test Success Criteria

With the power OFF and vehicle wiring disconnected, the negative and positive step data must meet predetermined Success Criteria.

A.7.6.2 Power On Success Criteria

With the power ON, vehicle wiring connected and umbilicals ON, there shall be no detectable steady state oscillation whose amplitude is greater than a signal of 100 millivolts peak-to-peak. Noise amplitude of 40 to 70 millivolts is allowable as characterized by the heavy white band (very high frequency) of noise as shown in photographs. Noise spikes of unsustained frequency with an amplitude of 180 millivolts are allowable. The damping ratio of each frequency component of each recorded transient response shall

be calculated using the following formula:

$$\text{Damping Ratio} = \frac{P\,(\ln 2\,E_i\; - (2.30))}{6.28\ t}$$

The value of damping ratio so calculated shall be recorded and shall be greater than 0.030. The following definitions apply to the above formula.

P = the period (in microseconds) of each frequency component. This shall be recorded for each frequency component of each transient response. It is expected that three to five identifiable frequency components will be observed.

t = the time (in microseconds) required for each identified frequency component to reach an amplitude of ten millivolts peak-to-peak. This shall be measured with respect to transient initiation.

E_i = the peak value (in millivolts) with respect to zero volts of the first cycle of the transient response of each frequency component. This shall be recorded for each frequency component of each transient response.

A.7.6.3 Umbilicals Disconnected

The same Success Criteria as in Paragraph A.7.6.2 above apply to this test.

A.8 SIGNAL INTERFACE TEST

A.8.1 Objective

To verify the electrical characteristics of the guidance signal interface prior to marriage of the MGC/DFCS.

A.8.2 Prerequisites

None required.

A.8.3 Configuration

MGC not connected.

A.8.4 Constraints

None required.

A.8.5 Test Description

A.8.5.1 Sequence System Load Test

The resistance shall be measured between the positive side of each discrete relay coil and the non-isolated discrete conductor at MGC cable connector. The polarity of the measurement shall be such that the resistance is measured for a current going from the positive side of the coil to the MGC discrete conductor.

A.8.6 Success Criteria

A.8.6.1 Sequence System Load Test

The resistance of the discrete relay coil shall be 64 to 711 Ohms. This measurement shall be made with sufficient voltage to overcome the steering diode breakout effects. The VECOS tape advance discrete load resistance shall be 700 ± 105 Ohms at the MGC connector. The FCS NO-GO discrete load resistance shall be 495 to 751 Ohms at the MGC connector.

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